Underwater Glider Dynamics and Control

Naomi Leonard
Department of Mechanical & Aerospace Engineering
Princeton University
Princeton, NJ 08544
phone: (609) 258-5129 fax: (609) 258-6109 email: naomi@princeton.edu

Grant Number: N000140210861
http://www.princeton.edu/~naomi

LONG-TERM GOALS

My long-term goal is to help improve versatility of underwater gliders as individual or networked platforms for ocean sampling and other applications by contributing to the development of a methodology for designing and analyzing high-performance, cost-effective underwater glider controllers.

OBJECTIVES

In this work, we build on our earlier results and accomplishments in understanding, modeling and controlling underwater glider dynamics (YIP Grant # N00014-98-1-0649). The focus is on dedicated gliding vehicles that have the ability to change mass (or volume) for buoyancy control and to redistribute mass (and possibly control a rudder) for attitude control. The framework consists of a dynamical systems model of underwater gliding vehicles together with techniques for generating and controlling glide maneuvers in the presence of uncertainty. The central objectives are as follows:

1. *Modelling and verification of underwater glider dynamics in three dimensions*. An important challenge here will be to build on our existing 3D dynamic model to best include hydrodynamic forces on a rigid body with wings in water. In this context we will seek to make the best use of experimental data from existing full-scale gliders as well as our own laboratory-scale underwater gliders.

2. *Nonlinear control design for underwater glider stabilization and tracking in three dimensions*. A key challenge is to design control algorithms that are consistent with the constraints and limits on control actuation (and sensing) in a buoyancy-propelled underwater glider. We will focus on gliders with fixed external surfaces, as well as those with a rudder, which can control buoyancy, e.g., through ballast change, and can control center of gravity, e.g., by means of mass redistribution.

3. *Coordinated control strategies for multiple vehicles and realization of these strategies on a network of buoyancy-controlled underwater gliders*. Significant challenges include designing coordination algorithms that are robust to failure and scalable with the number of vehicles. Further, the realization of techniques for glider dynamics will need to accommodate the very specialized way that buoyancy-controlled gliders can be made to maneuver.

4. *Demonstration and testing of glider control strategies*. We plan to test and demonstrate our strategies on gliders as part of the AOSN-II Monterey Bay Predictive Skills Experiment in the summer

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14. ABSTRACT

My long-term goal is to help improve versatility of underwater gliders as individual or networked platforms for ocean sampling and other applications by contributing to the development of a methodology for designing and analyzing high-performance, cost-effective underwater glider controllers.

15. SUBJECT TERMS

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of 2003, in experiments in Buzzards Bay, and elsewhere. We will also perform experiments on our laboratory-scale gliders.

APPROACH

The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. We have derived a dynamic glider model that describes a glider with simple body and wing shape (Leonard and Graver [2001]). Control is applied to two point masses inside the vehicle: the first point mass has variable mass but fixed position while the second point mass has fixed mass but variable position relative to the center of buoyancy. One control input changes the mass of the stationary point and another control force vector drives the movable mass. The model describes the nonlinear coupling between the vehicle and the shifting and changing mass. This model was derived for a glider in 3D and then specialized to motion in the vertical plane. The detailed model of lift and drag forces and viscous moment were introduced in the planar model. We will extend the viscous force/moment model to 3D and investigate if and how to modify the modelling of added mass/inertia terms so that the hydrodynamics of the rigid body with wings and tail are well approximated. We will study the stability and dynamics of steady and unsteady glide motions and maneuvers in 3D using this model. Experiments on our laboratory-scale vehicles and experimental data from operational gliders will be used in the continued derivation and validation of the glider model dynamics. Experiments will involve performance of steady glides, switches between glides and other unsteady glide maneuvers. The objective in these tests will be to take enough data for system identification purposes and for verification of model results, e.g., by comparing experimental data with simulation results. Wind tunnel testing has already been performed for a scale model of our laboratory glider ROGUE (Figure 1) in order to determine a lift and drag model (Graver et al [1998]). Further similar wind tunnel testing will be performed for other gliding bodies of interest.

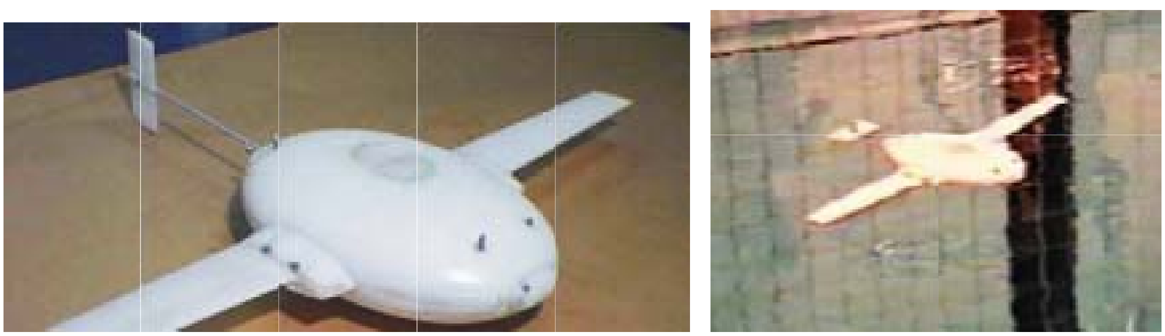

Figure 1: The Princeton laboratory-scale underwater glider, ROGUE. The hull is 18 inches long.

2. We have designed linear controllers and observers for stabilization of steady glide paths in the vertical plane (Leonard and Graver [2001], Graver and Leonard [2001]). These control laws already have the potential to make improvements over current practice on operational gliders. In principle, these model-based, feedback controllers require less experimentation and tuning and provide more robustness to fouling, payload changes and other uncertainties as compared to current techniques. Additionally, a dynamic observer estimates states that can be used to determine horizontal glider motion rather than the current methods that rely on assumptions of constant angle of attack. This can provide significant improvement to dead reckoning, to determination of flow velocity over glide cycles

as well as to control. We will extend these controllers and observers to full and simplified 3D glider models. This will allow, for example, control in the horizontal plane, e.g., waypoint following. We will also use nonlinear methods to derive control laws that are more versatile and overcome some of the limitations of approaches based on linearization. For example, nonlinear controllers could yield larger regions of attractions (i.e., stability guarantees on more global behavior). We will consider, for example, the energy-based design method referred to as the method of controlled Lagrangians that we have recently developed with colleagues for underactuated systems (see, for example, Bloch, Leonard and Marsden [2001]). The method of controlled Lagrangians is a control synthesis approach that provides a control law that modifies system energy so that the motion of interest is stable. The method is particularly well suited to underactuated systems, i.e., systems like underwater gliders that have fewer control inputs than system degrees of freedom. We will also consider optimal motion planning approaches for the glider (see, for instance, Chyba, Leonard and Sontag [2001]).

3. We will further develop our distributed approach to coordination of autonomous vehicle networks with a particular focus on realizing these strategies on underwater gliders which are underactuated and constrained systems. In earlier work we have developed coordinated control strategies for fully actuated point mass vehicle models that make use of artificial potentials and virtual leaders (see, for example, Leonard and Fiorelli [2001] and Ogren, Fiorelli and Leonard [2002]). Here, we will investigate how to extend this work so that we can guarantee network stability and performance for our underwater glider dynamics. For instance, one approach is to consider the point mass paths as motion plans for the gliders and use the low-level glider control to follow these paths. In Smith, Hanssmann and Leonard [2001], we investigated coordination of rigid bodies underwater notably focusing on the problem of alignment of vehicle orientations in 3D. This work will be integrated and extended.

4. We will adapt our model to operational gliders so that we can perform system identification, estimation of states, improved dead reckoning, improved control and network coordination in the AOSN-II Monterey Bay Predictive Skills Experiment in Summer 2003 as well as in experiments that will be run in preparation for this experiment. We have already begun to collaborate with Dave Fratantoni at WHOI who operates a fleet of gliders.

This project is led by N. Leonard (PI). R. Bachmayer (Research staff, Princeton) plays a key role in all aspects of this project, notably on the experimental and simulation side. J. Graver and P. Bhatta (graduate students) work on the gliding modelling, dynamics and control laws. E. Fiorelli (graduate student) studies the problem of designing coordinating control laws for multiple underwater gliders. R. Sorenson (Technical staff, Princeton) works on our laboratory-scale glider, .

WORK COMPLETED

This effort started late in FY002. Therefore, while several of the objectives discussed above have been initiated, none of the proposed work items is fully completed yet.

RESULTS

This effort started late in FY002; results will be forthcoming.

IMPACT/APPLICATIONS

The analysis and design methodology that we are developing for underwater glider dynamics and control will lead to a deeper understanding of how best to take advantage of the glider concept for ocean applications such as ocean sensing. Gliders have many useful features including low operational and capital costs, low noise and vibration, high reliability due to simplicity of design, minimal reliance on battery power, and low vulnerability of actuator mechanisms to the harsh effects of seawater. These features contribute to making the glider an economical, endurance ocean vehicle.

The advantages are expected to be greatest when multiple gliders are operated cooperatively in a network. With robust individual glider control and coordinating control design it is possible that networks of gliders can achieve highly efficient and adaptive group capabilities. This could lead to improved data-processing and decision-making capabilities which could have a major impact on missions such as adaptive ocean sampling.

TRANSITIONS

This effort started late in FY002 and so none of the planned transitions (for example, to the other AOSN-II teams) are completed yet.

RELATED PROJECTS

I participate in an NSF/KDI funded project joint with A.S. Morse (Yale), P. Belhumeur (Yale), R. Brockett (Harvard), D. Grunbaum (U. Washington) and J. Parrish (U. Washington) on coordination of natural and man-made groups. We are studying schooling of fish and "schooling" of autonomous underwater vehicles. A multiple-vehicle experimental testbed is being developed at Princeton. This project is related to the problem of coordination of groups of underwater gliders. See http://graham.princeton.edu/~auvlab/ and http://www.eng.yale.edu/grouper/

I participate in an AFOSR funded project on Coordinated Control of Groups of Vehicles. This is a joint project with V. Kumar and J. Ostrowski at University of Pennsylvania. A focus of the project is understanding cooperation in the context of coordinated control of distributed, autonomous agents, and the collection and fusion of the sensor information that they retrieve.

With my colleague Edward Belbruno, I have worked on a project for Global Aerospace Corporation (funded by NASA) on low-energy trajectory control of a stratospheric balloon network. The objective is to manage the geometry of the constellation of balloons for science and communication applications in the presence of a non-uniform flow field at 35 km altitude. The balloons can be controlled in a limited way with sails. This project is related to the problem of coordination of groups of underwater gliders introducing the specific problem of coping with a non-uniform flow field with underactuated vehicles.

I am working on controlling autonomous underwater vehicles with internal actuation as part of a project on stabilization of mechanical systems using controlled Lagrangians. This is a joint project with A.M. Bloch (U. Michigan), J.E. Marsden (Caltech), D.E. Chang (UCSB) and C.A. Woolsey (Virginia Tech).

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PUBLICATIONS

This effort started late in FY002, and so no papers funded by this project have appeared yet.